

# Discovery of a 0.02 Hz QPO feature in the Transient X-ray Pulsar KS 1947+300

Marykutty James<sup>1,2\*</sup>, Biswajit Paul<sup>2</sup>, Jincy Devasia<sup>1,2</sup> and Kavila Indulekha<sup>1</sup>

<sup>1</sup>*School of Pure and Applied Physics, Mahatma Gandhi University, Priyadarshini Hills P.O., Kottayam-686560, Kerala, India*

<sup>2</sup>*Raman Research Institute, Sadashivnagar, C. V. Raman Avenue, Bangalore 560080, India*

10 May 2010

## ABSTRACT

We report the discovery of Quasi Periodic Oscillations (QPO) at 0.02 Hz in a transient high mass X-ray binary pulsar KS 1947+300 using *RXTE*-PCA. The QPOs were detected during May-June 2001, at the end of a long outburst. This is the 9th transient accretion powered high magnetic field X-ray pulsar in which QPOs have been detected and the QPO frequency of this source is lowest in this class of sources. The unusual feature of this source is that though the outburst lasted for more than 100 days, the QPOs were detected only during the last few days of the outburst when the X-ray intensity had decayed to 1.6% of the peak intensity. The rms value of the QPO is large,  $\sim 15.4 \pm 1.0\%$  with a slight positive correlation with energy. The detection of QPOs and strong pulsations at a low luminosity level suggests that the magnetic field strength of the neutron star is not as high as was predicted earlier on the basis of a correlation between the spin-up torque and the X-ray luminosity.

**Key words:** X-ray: Neutron Stars - X-ray Binaries: individual (KS 1947+300)

## 1 INTRODUCTION

KS 1947+300 is an accretion powered X-ray pulsar which was first detected in June 1989 in observations made with the TTM coded-mask imaging spectrometer aboard the *Kvant* module of the *Mir Space Station* (Skinner 1989). The 2-27 keV flux was  $70 \pm 10$  mCrab. In two months the flux from the source faded by a factor of seven. Its X-ray spectrum could be described by a power law with photon index  $\Gamma = 1.72 \pm 0.31$  and a hydrogen column density  $N_H = (3.4 \pm 3.0) \times 10^{22}$  (Borozdin et al. 1990). The coordinates of the source were determined to be : R.A. =  $19^h 47^m 35^s.2$ , Dec. =  $+30^\circ 04' 47''$  (Eq. 1950.0). In April 1994, the Burst and *Burst and Transient Source Experiment* (BATSE) aboard the *Compton Gamma Ray Observatory* (CGRO) detected 18.7 s pulsations from an X-ray source within a few degrees of KS 1947+300. The newly detected source GRO J1948+32 was later found to be same as KS 1947+300 (Swank and Morgan 2000). The optical counterpart is a V=14.2 B0 Ve star with moderate reddening that indicates the distance to the system to be about 10 kpc (Negueruela et al. 2003).

One large outburst and several smaller outbursts of KS 1947+300 have been observed with the *Rossi X-ray Timing Explorer* (*RXTE*)-ASM. The first outburst of this source

was detected by *RXTE*-ASM in October 2000 (Levine and Corbet 2000). Following this the intensity declined, but the source became highly active again in November 2000. The outburst reached its peak in February 2001 and slowly declined till June 2001. Based on data acquired with *RXTE*-PCA during the 2000-2001 outburst, Galloway et al. (2004) determined the orbital parameters of the binary: the orbital period  $P_{orb} = 40.415 \pm 0.010$  d, the projected semi major axis  $a_x \sin i = 137 \pm 3$  lt-sec and eccentricity  $e = 0.033 \pm 0.013$ . Glitches are mainly observed in Anomalous X-ray Pulsars (AXP) and radio pulsars. But the *RXTE* analysis of this source revealed an increase in pulse frequency at an unusually high rate giving evidence for the first time for a glitch in an accretion powered pulsar (Galloway 2004). A broad band (0.1-100.0 keV) study of this source was first carried out with *BeppoSAX*. This revealed that the energy spectrum has three components - a Comptonized component, a 0.6 keV blackbody component, and a narrow and weak iron emission line at 6.7 keV (Naik et al. 2006). The absorption column density measured towards this source is low ( $4.0\text{-}5.0 \times 10^{21}$  atoms  $\text{cm}^{-2}$ ).

Quasi Periodic Oscillations (QPOs) in X-ray binaries are generally thought to be related to the rotation of the inner accretion disk (Paul & Rao 1998). Any inhomogeneous matter distribution or blobs of material in the inner disk may result in QPOs in the power spectrum. In the case of accretion powered X-ray pulsars this gives useful informa-

\* E-mail: marykuttykjames@yahoo.co.in

**Table 1.** List of PCA Observations

| Year | Obs Ids | No. of Pointings | Total Durations (ks) |
|------|---------|------------------|----------------------|
| 2000 | P50425  | 19               | 111.83               |
| 2001 | P50068  | 30               | 280.1                |
|      | P50425  | 18               | 73.7                 |
|      | P60402  | 53               | 162.8                |
| 2002 | P70404  | 15               | 46.3                 |

tion about the interaction between the accretion disk and the neutron star magnetosphere. Black hole X-ray binaries and low magnetic field neutron stars show QPOs over a wide range of frequency from a few Hz to a few hundred Hz. High magnetic field neutron star systems show only low frequency QPOs, in the range 10 mHz upto about 1 Hz. We have investigated the timing properties of the transient X-ray pulsar KS 1947+300 using observations made with the RXTE-PCA and report here the discovery of a transient QPO feature in this source.

## 2 OBSERVATIONS AND DATA

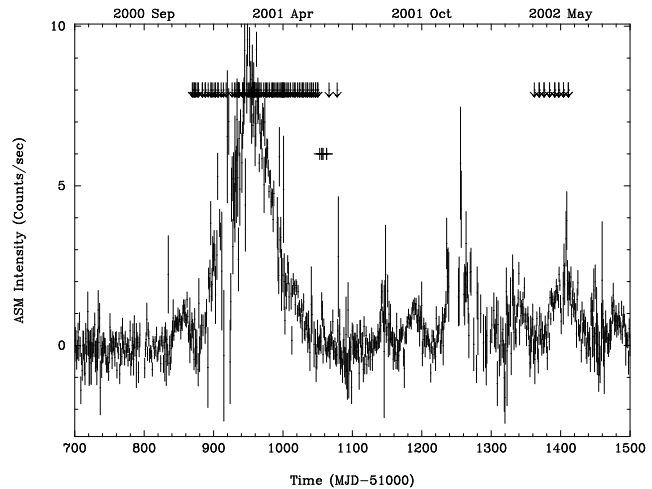
KS 1947+300 was observed extensively by *RXTE* during 2000-2002. *RXTE* carries three X-ray astronomy instruments. The All Sky Monitor (ASM) is sensitive to X-ray photons between 1.5 and 12 keV. The Proportional Counter Array (PCA) consists of five xenon proportional counter detectors, sensitive in the energy range of 2-60 keV with an effective area of 6500 cm<sup>2</sup> at 6 keV. The High Energy Timing Experiment (HEXTE) operates in the energy band of 15-250 keV.

In Figure 1 we show the one day averaged ASM light curve of this source during 2000-2002 in 1.5-12 keV energy band. In this period the source showed one large outburst that lasted for about four months, and several smaller outbursts. The first PCA observation of KS 1947+300 was performed in 2000 November 21. Subsequently, observations were made every 2 to 3 days until June 18 around when the main outburst ended. Some more PCA observations were carried out again in 2002, around a smaller outburst. A background subtracted lightcurve of the source made with data from one of the RXTE PCA detectors, PCU2 is shown in Figure 2. We have used all PCA observations of this source available in the archive.

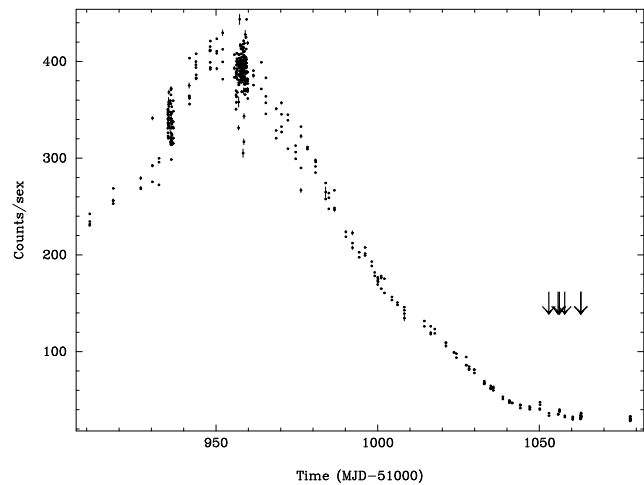
Any contamination from other sources are negligible because there is no known hard X-ray source within 2 degree from KS 1947+300. A total of 674 ks of useful data was obtained with the PCA from 135 observations. The details of the observations are given in Table 1.

### 2.1 Timing and Spectral Analysis

We extracted 2-60 keV light curves from the PCA observations using the Standard-1 mode data which has a time resolution of 0.125 s. To search for QPOs we created Power Density Spectra (PDS) using the FTOOL *powspec* for small

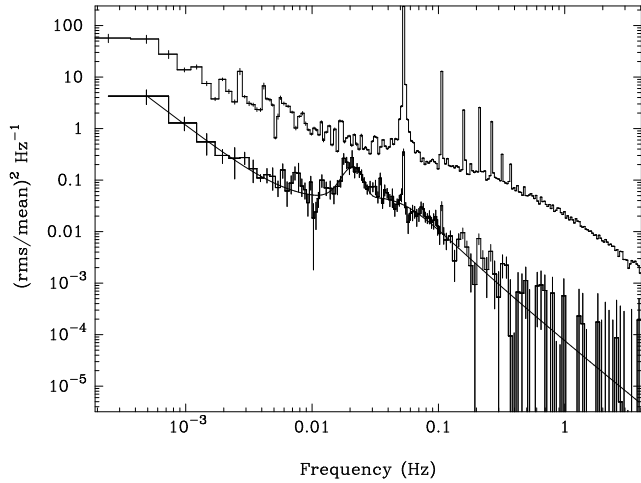


**Figure 1.** One day averaged *RXTE*-ASM light curve of KS 1947+300 during 2000-2002 in the 1.5-12 keV energy band. The vertical arrows indicate the times of the *RXTE*/PCA observations and the '+' signs indicate the period when the QPOs are detected.



**Figure 2.** Background subtracted light curve of KS 1947+300 obtained with *RXTE*-PCU2 during the 2001 outburst with a bin size of 800 s. The vertical arrows indicate the times of the QPO detection.

data segments of duration 2048 s. PDS from 5-10 consecutive segments were averaged to improve the detectability of any QPO like feature. The PDS were normalized such that their integral gives the squared rms fractional variability and the white noise level was subtracted. A narrow peak at around 0.055 Hz corresponding to the spin frequency of the pulsar and several harmonics are seen in all the PDS generated from the data of all the PCA observations in 2000-2002. In addition to the peaks due to the pulsations, a QPO feature is seen at  $0.0215 \pm 0.0007$  Hz in the 2001 May and June observations. The period during which the QPOs have been detected is also marked in Figure 1 and Figure 2. Two PDS, one obtained during the peak of the outburst and one with the QPO feature are shown in Figure 3. At first, we fitted the second PDS with two continuum components, a power-law and a Lorentzian and obtained a  $\chi^2$  of 178 for 110 degrees of freedom. The fit clearly showed the need for



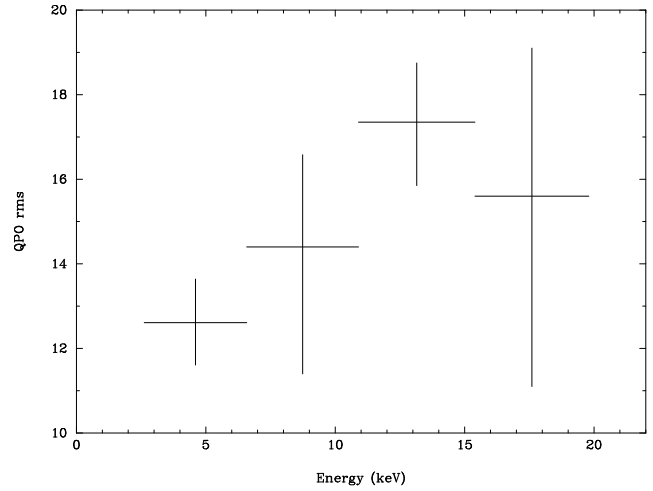
**Figure 3.** The power spectrum of KS1947+300 obtained during the peak of the outburst (top curve) and during the QPO detection period are shown here. The top curve has been multiplied by an arbitrary factor.

a third component around 0.2 Hz. With the addition of a third component, a gaussian, the  $\chi^2$  was reduced to 119 for 107 degrees of freedom. This improvement in  $\chi^2$  by 59 for the addition of one component is very significant. The ratio of the amplitude and the uncertainty of the gaussian component indicates a  $6\sigma$  detection of the QPO feature. The peaks corresponding to the pulsations are shown in Figure 3, but these were not included while fitting the PDS continuum. From the fitted power spectrum shown in Figure 3, and after correcting for the background count rate, we calculated the rms value of the QPO to be quite large,  $15.4 \pm 1.0\%$ . The Quality factor  $Q = \nu / \text{FWHM}$  of the 0.02 Hz QPO is 3.6, comparable to the quality factor of 4-10 in other HMXB pulsars. In PDS created with data segments of shorter duration the QPO feature has poor signal to noise ratio. However, by looking at the PDS averaged over smaller segments we have verified that the broad nature of the QPO seen in Figure 3 is intrinsic and it is not due to averaging of a narrow QPO feature with a variable frequency.

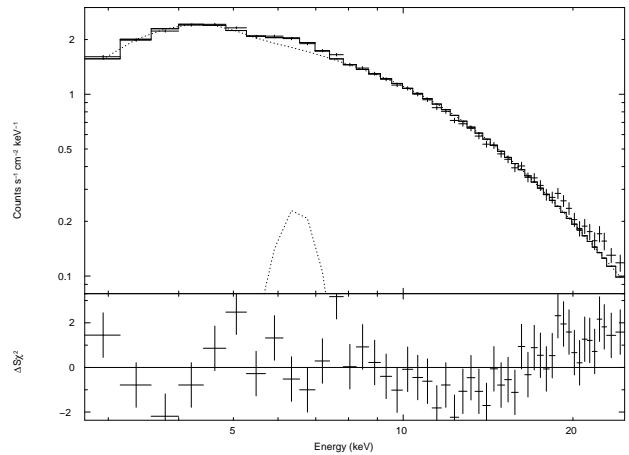
We have also calculated the energy dependence of the QPO feature. We created power spectra in different energy bands of 2.6-6.6, 6.6-11.0, 11.0-15.4 and 15.4-19.8 keV using event data from the PCA. There is marginal evidence for an increase in the rms value with energy and is shown in Figure 4. The PCA detectors have small effective area at higher energy and we did not detect the QPO feature above 20 keV.

To measure the X-ray flux during the period when QPOs are detected, we have generated an X-ray spectrum in 129 binned channels of the PCA observations. A model for the background spectrum was generated using *pcabackest* with appropriate background model provided by XTE guest Observer facility (GOF). We employed the caldb version 1.0.2 and the appropriate response matrix was generated for this observation using *pcarsp* version 11.7.

The spectrum is fitted with an absorbed power law and an iron emission line. The best fitted spectrum has



**Figure 4.** RMS fluctuation in the 0.02 Hz QPO is shown here as a function of energy.



**Figure 5.** The X-ray spectrum of KS 1947+300 is fitted with power law, absorption and a narrow emission line.

a photon index of  $1.44 \pm 0.02$  and an emission line with equivalent width of about  $200 \pm 37$  eV. The  $\chi^2_r$  value for the spectrum is 1.7 for 44 degrees of freedom. The flux in the 2-20 keV band during the time of the QPO detection is  $5.0 \times 10^{-11} \text{ erg cm}^2 \text{ s}^{-1}$ . The spectrum is shown in Figure 5 along with the best fit model and the residuals. The parameters of the best fitted model are given in Table 2.

**Table 2.** Best fit Spectral Parameters of KS 1947+300

| Parameter                       | Value                   |
|---------------------------------|-------------------------|
| $N_H (10^{22} \text{ cm}^{-2})$ | $2.43 \pm 0.4$          |
| Photon index                    | $1.44 \pm 0.02$         |
| norm                            | $0.0049 \pm 0.0006$     |
| Gaussian line (keV)             | $6.50 \pm 0.12$         |
| Equivalent width (keV)          | $0.2 \pm 0.037$         |
| Gaussian norm                   | $0.000055 \pm 0.000012$ |

### 3 DISCUSSION

We reported the detection of a low frequency QPO feature in the HMXB pulsar KS 1947+300 at  $\nu_{QPO} = 0.02$  Hz. The power density spectra of accretion powered pulsars consist of narrow peaks corresponding to the spin frequency of the pulsar and its harmonics, accompanied by aperiodic variabilities like broad bumps. QPOs have been detected in 16 accretion powered high magnetic field pulsars. These include many HMXBs and a few LMXBs; both transient and persistent. The list of transient and persistent sources with QPO features are given in Table 3. There are only three LMXB sources in which QPOs have been detected. Table 3 summarizes the QPO detections in high magnetic field accreting pulsars, giving spin frequency  $\nu_s$ , the observed QPO frequency  $\nu_{QPO}$ , and ratio of the two. The frequency of the QPO feature, detected in KS 1947+300 is lowest among the transient X-ray pulsars.

Various models have been proposed to explain the sub-Hz QPO features in high mass X-ray binaries. Among the most popular models are the Magnetospheric Beat Frequency Model (MBFM; Alpar and Shaham 1985) and the Keplerian Frequency Model (KFM; van der Klis et al. 1987). In the KFM the QPOs arise from the modulation of the X-rays by inhomogeneities in the accretion disk, at the Keplerian frequency. In the MBFM, the QPO frequency is the difference between the spin frequency and the Keplerian frequency of the inner edge of the accretion disk  $\nu_{QPO} = \nu_k - \nu_s$  (Shibazaki & Lamb 1987). Mass flow to the neutron star is expected to be stopped at magnetospheric boundary by centrifugal inhibition of accretion if the Keplerian frequency at the magnetospheric boundary is less than the neutron star spin frequency (Stella et al. 1986). Among the sources listed in Table 3, the KFM is not applicable for some of the sources including KS 1947+300 as the observed QPO frequency is smaller than the pulse frequency. At larger mass accretion rate, the accretion disk is expected to extend closer to the neutron star, and therefore, in either model, a positive correlation is expected between the QPO centroid frequency and the X-ray intensity (Finger 1998). In some sources, the QPO frequency is found to be quite constant with more than a factor of 10 variation in X-ray luminosity. In some of these sources, it is believed that the inner disk origin may not be applicable while in some other sources there are a variety of other reasons for a lack of correlation (Raichur & Paul 2008a,b).

A positive energy dependence of the QPO rms, similar to that seen in KS 1947+300 is found in some sources (XTE J1858+034, Paul & Rao 1998). This favours the MBFM over the KFM, while the QPO rms is independent of the energy in the persistent X-ray pulsar Cen X-3 (Raichur & Paul 2008a).

With some exceptions (4U 1626-67; Kaur et al. 2008 but see also Jain et al. 2009), the QPOs are transient phenomena in all types of pulsars. The persistent X-ray pulsars do not show persistent QPOs (Raichur & Paul 2008a). In the transient X-ray pulsars that show QPOs, the feature is not detected in all the outbursts. For example the recent outbursts of the source A 0535+262 does not

show the flux dependent QPO features that was observed with BATSE during a large outburst in 1994 (Finger et al. 1996). However, if QPOs are present during an outburst, it is usually present throughout the outburst (Finger et al. 1996, Mukherjee et al. 2006). In the case of KS 1947+300, the QPO feature was not seen in 2000 and 2002 data. It appeared very near the end of the 2001 outburst during MJD 52052-52062. We also analysed the 2-20 keV spectrum during the peak of the outburst and the flux measured is  $3 \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$ . The QPO feature is seen to be present when the X-ray flux had dropped to 1.6% of this peak value.

Assuming MBFM for KS 1947+300, the Keplerian frequency of the inner disk corresponding to a 0.02 Hz oscillation is  $\nu_k = 0.02 + 0.053 = 0.073$ . Thus the radius of the inner accretion disk can be estimated as

$$R_{BFM} = \left( \frac{GM}{4\pi^2(\nu_{QPO} + \nu_s)^2} \right)^{1/3} \quad (1)$$

The  $R_{BFM}$  obtained for a mass of  $1.4M_\odot$  is  $9.6 \times 10^3$  km. The X-ray flux of KS 1947+300 in the 2-20 keV band is  $5.0 \times 10^{-11}$  erg cm $^{-2}$  s $^{-1}$  during the time of QPO detection. This flux amounts to an X-ray luminosity of  $0.6 \times 10^{36}$  erg s $^{-1}$  for a source distance of 10 kpc. Using a correlation between the spin-up torque and the broad band X-ray luminosity of this source a very strong magnetic field of  $B = 2.5 \times 10^{13}$  G was inferred for the neutron star (Tsygankov & Lutovinov 2005). Using the above, and canonical values for the stellar radius and mass of 10 km and  $1.4 M_\odot$  respectively, the size of the magnetosphere for a dipole field configuration can be estimated as (Ghosh & Lamb 1991)

$$R_m = 2.4 \times 10^3 (M/1.4M_\odot)^{1/7} \times (B/2.5 \times 10^{12} \text{G})^{4/7} \times (R/10^6 \text{cm})^{10/7} \times (L_x/3.1 \times 10^{37} \text{ergs s}^{-1})^{-2/7} \text{km} \quad (2)$$

The magnetospheric radius is obtained as  $2.76 \times 10^4$  km.

Although the magnetic field value is rather uncertain, such a strong magnetic field implies a magnetospheric radius larger by a factor of 2.8 compared to the inner disk radius at which the QPOs are likely to be produced in the MBFM and by a factor of 2 compared to the corotation radius. This is true even if we assume a 50% bolometric correction, 12% larger distance (Kiziloglu et al. 2007) and the neutron star mass and radius larger by 20% (Lattimer & Prakash 2007). If the magnetic field is so strong, the X-ray flux value during the QPO detection indicates that the source should be in propeller regime. The presence of QPOs and the strong pulsations at the low flux value thus suggests that the magnetic field may not be as high as was suggested by Tsygankov & Lutovinov (2005). On the other hand, for an X-ray luminosity of  $0.6 \times 10^{36}$  erg s $^{-1}$   $d_{10\text{kpc}}^2$  if the observed QPOs are produced due to inhomogeneities near the magnetospheric radius, it implies a magnetic field strength of about  $B = 4 \times 10^{12}$  d $_{10\text{kpc}}$  G for the neutron star. The X-ray spectrum of KS 1947+300, however, is devoid of any cyclotron absorption line corresponding to such a magnetic field strength (Naik et al. 2006).

#### 4 ACKNOWLEDGEMENTS

We thank an anonymous referee for many suggestions that helped us to improve the paper. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

#### REFERENCES

- Alpar, M. A., & Shaham, J., 1985, *Nature*, 316, 239  
Angelini, L., Stella, L., Parmar, A.N., 1989, *ApJ*, 346, 906  
Angelini, L., White, N.E., Stella, L., Parmar, A.N., 1991, *ApJ*, 371, 332  
Borozdin, K., Gil'fanov, M., et al. 1990, *SvAL*, 16, 345B  
Finger, M. H., Wilson, R. B., & Harmon, B. A., 1996, *ApJ*, 459, 288  
Finger, M. H., 1998, *AdSpR*, 22, 1007  
Galloway, D. K., Morgan, E. H., Levine, A.M., 2004, *ApJ*, 613, 1164  
Ghosh, P., Lamb, F.K. 1991, in *Neutron Stars Theory and Observation*, eds. J. Ventura and D. Pines, NATO ASI Series 43, 363  
Inam, S. C., Baykal, A., Swank, J., Stark, M. J., 2004, *ApJ*, 616, 463  
In't Zand, J. J. M., Baykal, A., & Strohmayer, T.E., 1998, *ApJ*, 496, 386  
Jain, Chetana., Paul, Biswajit., & Dutt, Anjan., 2009, arXiv:0906.4169[astro-ph.HE]  
Kaur, R., Paul, B., Raichur, H. & Sagar, R., 2007, *ApJ*, 660, 1409  
Kaur, R., Paul, B., Kumar, B., & Sagar, R., 2008, *ApJ*, 676, 1184  
Kiziloglu, U., Baykal, A., & Kiziloglu, N., 2007, *AN*, 328, 142  
Lattimer, James M., & Prakash, Madappa 2007, *PhR*, 442, 109  
Levine, A., & Corbet, R., 2000, *IAU, Circ.*, No.7523  
Mukherjee, U., Bapna, S., Raichur, H., Paul, B., & Jaaffrey, S. N. A., 2006, *JApA*, 27, 25  
Moon, D., Eikenberry, Stephen. S., 2001a, *ApJ*, 549, L225  
Moon, D., Eikenberry, Stephen. S., 2001b, *ApJ*, 552, L135  
Naik, S., Callanan, P.J., Paul, B., & Dotani, T., 2006, *ApJ*, 647, 1293  
Negueruela, I., Israel, G. L., et al., 2003, *A&A*, 397, 739  
Paul, B., & Rao, A. R., 1998, *A&A*, 337, 815  
Raichur, Harsha, Paul, Biswajit, 2008a, *ApJ*, 685, 1109  
Raichur, Harsha, Paul, Biswajit, 2008b, *MNRAS*, 387, 439  
Shibazaki, N., & Lamb, F. K., 1987, *ApJ*, 318, 767  
Shinoda, K., Kii, T., et al., 1990, *PASJ*, 42, L27  
Skinner, G. K., 1989, *IAUC*, 4850  
Soong, Y., & Swank, J.H., 1989, *ESASP*, 296, 617  
Stella, L., N.E. White, and R. Rosner, 1986, *ApJ*, 308, 669  
Swank, J., & Morgan, E., 2000, *IAUC*, 7531  
Takeshima T., Dotani T., Mitsuda K., Nagase F., 1991, *PASJ*, 43, L43  
Takeshima T., Dotani T., Mitsuda K., Nagase F., 1994, *ApJ*, 436, 871  
Takeshima T., 1997, *BAAS*, 191, 111.04  
Tsygankov, S. S.; Lutovinov, A. A., 2005, *Astronomy Letters*, 31, 88  
van der Klis, M., Stella, L., White, N., Jansen, F., & Parmar, A.N., 1987, *ApJ*, 316, 411  
Zhang, W., Morgan, E.H., et al. 1996, *ApJ*, 469, L29

**Table 3.** List of QPO sources

| Source             | Type | $\nu_s$<br>(mHz) | $\nu_{QPO}$<br>(mHz) | $\nu_{QPO}/\nu_s$<br>(mHz) | Reference <sup>1</sup> |
|--------------------|------|------------------|----------------------|----------------------------|------------------------|
| Transient pulsars  |      |                  |                      |                            |                        |
| KS 1947+300        | HMXB | 53               | 20                   | 0.38                       | This work              |
| SAX J2103.5+4545   | HMXB | 2.79             | 44                   | 15.77                      | 1                      |
| A0535+26           | HMXB | 9.7              | 50                   | 5.15                       | 2                      |
| V0332+53           | HMXB | 229              | 51                   | 0.223                      | 3                      |
| 4U 0115+63         | HMXB | 277              | 62                   | 0.224                      | 4                      |
| XTE J1858+034      | HMXB | 4.53             | 110                  | 24.3                       | 5                      |
| EXO 2030+375       | HMXB | 24               | 200                  | 8.33                       | 6                      |
| XTE J0111.2-7317   | HMXB | 32               | 1270                 | 39.68                      | 7                      |
| GRO J1744-28       | LMXB | 2100             | 20000                | 9.52                       | 8                      |
| Persistent pulsars |      |                  |                      |                            |                        |
| SMC X-1            | HMXB | 1410             | 10                   | 0.0071                     | 9                      |
| Her X-1            | LMXB | 806              | 13                   | 0.016                      | 10                     |
| LMC X-4            | HMXB | 74               | 0.65-20              | 0.0087-0.27                | 11                     |
| Cen X-3            | HMXB | 207              | 35                   | 0.17                       | 12                     |
| 4U 1626-67         | LMXB | 130              | 48                   | 0.37                       | 13                     |
| X Per              | HMXB | 1.2              | 54                   | 45                         | 14                     |
| 4U 1907+09         | HMXB | 2.27             | 69                   | 30.4                       | 15                     |

References: (1) Inam et al. 2004; (2) Finger et al. 1996; (3) Takeshima et al. 1994; (4) Soong & Swank 1989; (5) Paul & Rao, 1998; (6) Angelini et al. 1989; (7) Kaur et al. 2007; (8) Zhang et al. 1996. (9) Angelini et al. 1991; (10) Moon et al. 2001b; (11) Moon et al. 2001a; (12) Takeshima et al. 1991; (13) Shinoda et al. 1990; (14) Takeshima 1997; (15) In't Zand et al. 1998;